Cairo University

THREE-DIMENSIONAL NUMERICAL STUDY OF SUBMERGED SPATIAL HYDRAULIC JUMPS

By

Eng. **Ahmed Safaa Foda**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Irrigation and Hydraulics Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Under the Supervision of

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Title of Thesis:

Three-Dimensional Numerical Study of Submerged Spatial Hydraulic Jumps

Key Words:
Abrupt channel expansion, submerged spatial hydraulic jump, asymmetric jump, oscillatory jump, computational fluid dynamics

Summary:

A three-dimensional numerical model was applied to simulate submerged spatial hydraulic jumps (SSHJ) downstream of a symmetric vent that discharges into a wider channel. Simulations were carried out for different aspect ratios of the vent, expansion ratios of vent width to downstream channel width, tailwater depth, and inlet Froude number. Depending on these factors, simulations indicated the formation of steady asymmetric SSHJ, oscillatory asymmetric SSHJ, and steady symmetric SSHJ, consistent with results of previous experimental studies. The model reproduced observed depth downstream of vent, jump length, and velocity profiles along channel centerline for steady symmetric SSHJ. For oscillatory asymmetric SSHJ, simulated oscillation frequencies had corresponding Strouhal numbers that varied with expansion ratio and ranged between 0.003 and 0.015. With piers downstream of the vent, oscillatory SSHJ continued to exhibit jet deflections when pier length was relatively short ($\lesssim$0.2 of jump length) but became steady asymmetric for longer piers. Numerical simulations with end sill downstream of the vent were conducted. End sill proved to be an efficient tool in stabilizing oscillatory SSHJ and reducing jump roller length.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: **Ahmed Safaa Abdo Foda** Date:

Signature:

Dedication

To my beloved family

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Nomenclature

b = vent width (m)

B = channel width (m)

F_r = Froude Number (-)

f_v = volume of fluid

g = gravitational acceleration (ms^{-2})

h = vent height (m)

H_l = head loss (m)

H_o = total head at vent outlet (m)

L_p = pier length (m)

L_r = jump roller length (m)

R_e = Reynolds number (-)

S_t = Strouhal number (-)

U = velocity through inlet vent (ms^{-1})

u_o = observed velocity (ms^{-1})

$\overline{u_o}$ = average velocity (ms^{-1})

u_s = simulated velocity (ms^{-1})

y_t = tailwater depth (m)

Y_t = tailwater depth to vent height ratio (-)

α = expansion ratio (-)

β = vent aspect ratio (-)

ν = kinematic viscosity of water (m^{2}s^{-1})

$LS =$ End sill location ratio (-)

$HS =$ End sill height ratio (-)

$\delta =$ End sill height to location ratio (-)

Abstract

Hydraulic jumps in open channels have an important role in energy dissipation downstream of hydraulic structures. The hydraulic jump roller dissipates energy from supercritical flow shooting out of structure vents and transforms it to less erosive subcritical flow. Depending on the location of the jump roller relative to structure vents, different types of hydraulic jumps may occur including repelled jumps, transitional jumps, and spatial jumps. The focus of this study is the spatial hydraulic jump which forms entirely in the wider channel immediately downstream of piers. In particular, we focus on the submerged spatial hydraulic jump (SSHJ) which forms when vertical vent gates are located at the downstream end of piers, tail-water depth is large enough to submerge the hydraulic jump, and water depth immediately downstream of vents exceeds vent height. SSHJ might be steady symmetric, steady asymmetric, or oscillatory depending on expansion ratio, vent aspect ratio, and tail-water depth.

To our knowledge, numerical investigation of hydraulic jump characteristics has been limited to free and submerged classical hydraulic jumps without width expansions. The main objective of this study is to extend the previous numerical studies to submerged spatial hydraulic jump (SSHJ). In particular, this study tests the ability of available 3D numerical models to reproduce characteristics and types of SSHJ observed in previous experimental studies.

A three-dimensional numerical model was applied to simulate submerged spatial hydraulic jumps (SSHJ) downstream of a symmetric vent that discharges into a wider channel. Simulations were carried out for different aspect ratios of the vent, expansion ratios of vent width to downstream channel width, tail water depth, and inlet Froude number. Depending on these factors, simulations indicated the formation of steady asymmetric SSHJ, oscillatory asymmetric SSHJ, and steady symmetric SSHJ, consistent with results of previous experimental studies. The model reproduced observed depth downstream of vent, jump length, and velocity profiles along channel centerline. A degree of symmetry index based on longitudinal velocity distribution ranged between 70% and 100% for steady asymmetric and symmetric SSHJ. For oscillatory asymmetric SSHJ, simulated oscillation frequencies had corresponding Strouhal numbers that varied with expansion ratio and ranged between 0.003 and 0.015. With the existence of piers downstream of the vent, oscillatory SSHJ continued to exhibit jet deflections when pier length was relatively short ($\lesssim$0.2 of jump length) but became steady asymmetric for longer piers. This study improves the understanding of oscillatory SSHJ and indicates that three-dimensional numerical models are able to reproduce SSHJ formation downstream of hydraulic structures.

To reduce the length of SSHJ and cost of stilling basin containing the jump, an end sill was added to the model. Stability of submerged spatial hydraulic jumps below abrupt symmetric expansions are numerically studied for basins with and without end sills. Numerical simulation for one expansion ratio, and different solid sill heights and locations were conducted. The two parameters (sill height and sill location) were found to play an important role in the hydraulic jump's configuration, energy dissipation, and flow patterns. End sill proved to be an efficient tool in stabilizing oscillatory submerged spatial hydraulic jump and reducing the jump length.